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Implementation of a Robust 2400 b/s LPC Algorithm for Operation in Noisy Environments

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1 April 1987

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LEXINGTON, MASSACHUSETTS

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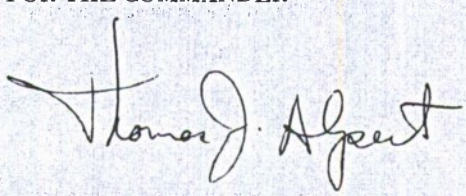
FOR THE COMMANDER



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IMPLEMENTATION OF A ROBUST 2400 b/s LPC ALGORITHM FOR OPERATION IN NOISY ENVIRONMENTS

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ABSTRACT

A detailed description of the implementation of a robust 2400 b/s LPC algorithm is presented. The algorithm was developed to improve vocoder performance in acoustically compromised environments. Improved robustness in noise is achieved by (1) increasing the speech bandwidth to 5 kHz, (2) increasing the LPC model order to 12, and (3) doubling the analysis rate. Frame fill techniques are used to achieve the 2400 b/s data rate. The algorithm is embodied in the Advanced Linear Predictive Coding Microprocessor which was developed as a prototype voice processor for in-flight evaluation of narrowband voice communication in the JTIDS communication system.

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1. INTRODUCTION

This report presents a detailed description of a 2400 b/s LPC vocoder algorithm designed for operation in noisy environments. The algorithm was developed as part of an effort to provide narrowband digital voice equipment for the JTIDS communication system. Candidates for JTIDS terminals include selected airborne platforms (E-3A, F-15) and ground installations. The F-15 fighter aircraft acoustic environment is especially harsh and may seriously degrade vocoder performance. Other operating conditions such as pilot stress and facemask-induced distortions may further degrade the acoustic signal. As part of the program, steps were taken at Lincoln Laboratory to modify the basic LPC algorithm so as to make it less vulnerable to acoustic distortions and to improve speech intelligibility in acoustically compromised environments. The resulting algorithm is embodied in the Advanced Linear Predictive Coding Microprocessor[1] which was developed as a prototype voice processor for in-flight evaluation of narrowband voice communication in the JTIDS communication system.

Studies indicated that several modifications could be made to the basic LPC algorithm to improve its robustness in noisy environments. These include (1) increasing the speech bandwidth to 5 kHz using a 10 kHz sampling clock, (2) increasing the LPC model order from 10 to 12, (3) applying the full model in both voiced and unvoiced frames, (4) using analog pre-emphasis and de-emphasis, and (5) doubling the analysis rate using a 50 percent overlapped autocorrelation window. Ordinarily these steps would cause the data rate to increase to 4800 b/s or more. The 2400 b/s data rate is retained by using a frame fill approach in which alternate data transmission frames are replaced by a small number of control bits which are used by the receiver to reconstruct the missing frames.[2] Note that these modifications lead to an algorithm which is not interoperable with the DoD standard LPC-10 (Reference 3).

Extensive testing of a variety of narrowband algorithms was performed using DRT source material recorded in a simulated F-15 high noise environment (115 dBA SPL). A complete description of these tests is found in Reference 4. The DRT results for algorithms of interest were:

DoD LPC-10 (Reference 3)	71.1
Lincoln LPC (Reference 5)	75.2
Robust LPC (2600 b/s)	80.6

The "Lincoln LPC" is a 10th order autocorrelation type vocoder which uses a Gold pitch detector and lattice synthesizer. The speech bandwidth in the Lincoln LPC is 4 kHz and the analysis frame is 20.5 ms. The "Robust LPC" was originally implemented at 2600 b/s on the Lincoln Digital Signal Processor and incorporated the modifications referred to earlier. This algorithm was further modified to run at 2400 b/s on the ALPCM and produced a DRT score of 79.9 for the same F-15 high noise condition. The remainder of this document is devoted to a detailed description of the implementation of the 2400 b/s robust LPC algorithm.

2. ALGORITHM CHARACTERISTICS AND BIT ASSIGNMENTS

The robust LPC algorithm is an extension of the basic Lincoln 10th order LPC. Table I describes the characteristics of the two algorithms and Table II presents the bit assignments. The bit assignments for the high performance algorithm are identical to those for the basic algorithm but allocate 2 bits each for k_{10} and k_{11} and 5 bits for the control word.

TABLE I

Characteristics of the Lincoln LPC Algorithms

Characteristic	Basic Lincoln LPC	High Performance Lincoln LPC
Speech Bandwidth	4 kHz	5 kHz
Analysis Frame	20.5 ms, No Overlap	24 ms 50% Overlap
Bits/Frame	49	58
LPC Model Order	10 Pole, Voiced and Unvoiced	12 Pole, Voiced and Unvoiced
Error Correction	No	No

The serial bit stream is transmitted in the order shown in Table II, with the sync bit transmitted first and the control word last. All words are transmitted LSB first.

3. FRAME FILL STRATEGY AND CODING

The frame fill strategy presented in this report is modified from Reference 2 where frame fill was employed to reduce the data rate of a DoD standard LPC-10 to 1200 b/s. The notation used in this section consists of a parameter followed by a numerical suffix which represents a reverse time order frame index. Thus the parameter "x" for the frames of interest is x4, x3, x2, x1, and x0 in temporal order with x0 representing the most recent value. The parameter sets for the even frames are transmitted fully and frame 1 is the frame (currently) to be filled.

The control word consists of 5 bits from which alternate frames are synthesized at the receiver. Bit allocation is as follows: pitch (1 bit), energy (2 bits), spectrum (2 bits). The individual bits in the control word are represented as vb1, e1, e0, s1, s0, where vb1 is the MSB and s0 is the LSB. The remainder of this section will describe the construction of the 5-bit control word. The coding and decoding tables referred to in this section can be found in the Appendix.

TABLE II

Bit Assignments for the Lincoln LPC Algorithms

Parameter	Basic LPC	High Performance LPC
Sync	1	1
Pitch	7	7
Energy	5	5
k_0	6	6
k_1	6	6
k_2	4	4
k_3	4	4
k_4	3	3
k_5	3	3
k_6	3	3
k_7	3	3
k_8	2	2
k_9	2	2
k_{10}	0	2
k_{11}	0	2
Control	0	5

3.1 Pitch

Frame fill of the pitch and voicing parameter requires transmission of only one voicing bit for the filled frame. (The 2400 b/s system used here, unlike the DoD LPC-10, has no voicing

transition states. All received transition states are mapped to unvoiced). The pitch and voicing are inferred at the receiver from the following table:

Voicing Sequence qp2, vb1, qp0	Inferred Pitch/voicing
u u u	qp1 = u
u u v	qp1 = u
u v u	qp1 = u
u v v	qp1 = qp0
v u u	qp1 = u
v u v	qp1 = (qp2+qp0)/2
v v u	qp1 = qp2
v v v	qp1 = (qp2+qp0)/2

where:

qpn = quantized pitch for frame n (i.e., the value of pitch available to the receiver)
vb1 = voicing control bit for frame 1 (vb1 = 1 for voiced)
v = voiced
u = unvoiced

The inferred pitch value for the v-u-v sequence is a judgment based upon the assumption that this sequence represents a voicing detection or data transmission error.

The pitch detector implemented in the high performance algorithm accepts values between 28 and 174 samples inclusive (2.8 to 17.4 ms) as representing legitimate voiced speech frames. Pitch values outside this range are assumed to represent unvoiced frames and are coded to zero. Pitch candidates for the voiced frames are coded to 6 bits directly via the 147-entry lookup table *ptbl*. The 6-bit pitch code word is decoded at the receiver using the table *dptbl*. Note that although the current vocoder implementation allocates 7 bits to the pitch field, only the least significant 6 bits contain the pitch code word. The upper bit is ignored.

3.2 Energy

In the Lincoln algorithm the value transmitted for the frame energy is derived from the residual energy as determined from the LeRoux-Gueguen recursion. The energies are encoded via the 31-entry coding table *etbl* and decoded using *detbl*. Coding using *etbl* is logarithmic and thus provides finer resolution at lower energy values than at higher ones. The decoding table *detbl* presents the synthesizer with amplitude rather than energy and thus eliminates the need for a square root routine.

The filled-frame energy is the closest of four values to the actual value based on a comparison of the log energies (i.e., the closest value on a dB scale). Since the receiver can only have choices generated from quantized values it has received during the even frames, these quantized

values are generated in the transmitter for comparison to the unquantized value from the analyzer frame to be interpolated. A computationally expedient way of approximating this comparison is to first encode all the energies (from the odd numbered transmitter frame plus the four candidates) using table *etbl* to provide a 5-bit approximation to the logs, and to then perform the search for the minimum absolute distance between the log energy of the odd numbered transmitter frame and the four candidates using these 5-bit values. The energy value for the interpolated frame is then coded to 2 bits. These are the four energy choices:

Candidate	**Code (control) value**
E0	0 (el = 0, e0 = 0)
E2	1 (el = 0, e0 = 1)
geometric mean (E0,E2)	2 (el = 1, e0 = 0)
min (max(E0,E2) + 3dB, E_{max})	3 (el = 1, e0 = 1)

The last candidate is intended to aid representation of short energy bursts which are surrounded by lower energy regions. It amounts to the greater of the adjacent frame amplitudes plus 3 dB subject to the limitation that it not exceed the range of the coding table. The metric is chosen to mimic human amplitude perception. The third choice is chosen to approximate a perceptual midpoint between the first and second choices and is computed using the 5-bit log energy values:

$$\text{log geometric mean } [E_0, E_2] = \frac{\log E_0 + \log E_2}{2}$$

3.3 Spectrum

The spectrum parameters consist of the first 12 reflection coefficients derived from an autocorrelation-type linear predictive analysis of the input speech. There are 4 coding tables used to encode the reflection coefficients: *lar6*, *lar4*, *lar3*, and *lar2*. The suffix indicates the number of bits to which the parameter will be encoded by a given table. Thus *lar6* is used to encode k_0 and $-k_1$ to 6 bits; *lar4* to encode k_2 and k_3 to 4 bits; *lar3* to encode k_4, k_5, k_6, and k_7 to 3 bits; and *lar2* to encode k_8, k_9, k_{10}, and k_{11} to 2 bits. The corresponding decoding tables are *dlar6*, *dlar4*, *dlar3*, and *dlar2*. Each of the *lar* tables is designed for use only with the indicated k_i (they were determined from individual parameter histograms). It has been found empirically that the histogram for k_1 is approximately the reverse of that for k_0. Thus the tables *lar6* and *dlar6* can be applied if k_1 is negated before coding and after decoding.

The filled spectrum (K vector) is one of four choices as determined by using a weighted, squared-Euclidean metric with reflection coefficients represented by the corresponding LARs (log-area ratios):

$$d(J,FF) = \sum_{i=0}^{11} \{w[i] * (J[i] - FF[i])^2\}$$

where

J[i] = LAR form of the candidate receiver interpolation vector, $0 \leqslant i \leqslant 11$

FF[i] = LAR form of the vector at the transmitter for interpolated frame, $0 \leqslant i \leqslant 11$

w[0] = 1

w[i] = $1 - (i-1)/16$, $1 \leqslant i \leqslant 11$

The four choices for the candidate receiver interpolation vector at the receiver are:

Candidate	**Code (control) value**	
qK0	0	(s1 = 0, s0 = 0)
L_{avg}(qK0,qK2)	1	(s1 = 0, s0 = 1)
qK2	2	(s1 = 1, s0 = 0)
qK4	3	(s1 = 1, s0 = 1)

where

qKn = quantized K vector for frame n
sl,s0 = spectrum control bits
$L_{avg}(X,Y) = LAR^{-1}((LAR(X)+LAR(Y))/2)$
(componentwise for the vectors X and Y)

The first, third, and fourth choices represent the vectors from neighboring frames. The second choice represents an "average" spectrum where the averaging takes place in the LAR domain.

The candidate vectors are constructed at the transmitter by first encoding and decoding the reflection coefficients k_i using the appropriate *lar* and *dlar* tables and then forming the corresponding LAR vectors from these quantized values. The LARs are approximated by the 256 entry table *lartab* which spans k = –0.98 to k = 0.98 in uniform increments of log-area-ratio. The 8-bit index to the table serves as the approximate LAR value of the corresponding quantized reflection coefficient.

4. SUMMARY

A detailed description of the implementation of the Lincoln 2400 b/s high performance LPC algorithm has been presented in this report. The algorithm relies on higher sampling and analysis rates to improve vocoder performance in acoustically compromised environments. Frame fill methods are used to achieve the 2400 b/s data rate. The algorithm has been implemented in the Advanced Linear Predictive Coding Microprocessor which has been integrated into the JTIDS communication environment.

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APPENDIX
CODING AND DECODING TABLES

```
;pitch coding table @100usec, entries are octal values

ptbl    1   ;pitch=28.   36              56              70
        2                36              56              70
        3                37              56              70
        4                37              56              70
        5                40              57              71
        6                40              57              71
        7                41              57              71
        10               41              57              71
        11               42              60              72
        12               42              60              72
        13               43              60              72
        14               43              60              72
        15               44              61              73
        16               44              61              73
        17               45              61              73
        20               45              61              73
        21               46              62              74
        22               46              62              74
        23               47              62              74
        24               47              62              74
        25               50              63              75
        26               50              63              75
        26               51              63              75
        27               51              63              75
        27               52              64              76
        30               52              64              76
        30               53              64              76
        31               53              64              76
        31               53              65              77
        32               53              65              77
        32               54              65              77
        33               54              65              77
        33               54              66
        34               54              66
        34               55              66
        35               55              66
        35               55
                         55                                      ;pitch=174.
```

```
;pitch decoding table @100usec

dptbl   0.
        28.                     70.
        29.                     72.
        30.                     74.
        31.                     76.
        32.                     78.
        33.                     80.
        34.                     82.
        35.                     84.
        36.                     86.
        37.                     88.
        38.                     90.
        39.                     93.
        40.                     97.
        41.                     101.
        42.                     105.
        43.                     109.
        44.                     113.
        45.                     117.
        46.                     121.
        47.                     125.
        48.                     129.
        50.                     133.
        52.                     137.
        54.                     141.
        56.                     145.
        58.                     149.
        60.                     153.
        62.                     157.
        64.                     161.
        66.                     165.
        68.                     169.
                                173.
```

```
;energy encoding table

etbl    .000122.
        .000163.
        .000218.
        .000292.
        .000390.
        .000522.
        .000698.
        .000933.
        .001248.
        .001669.
        .002233.
        .002986.
        .003993.
        .005340.
        .007142.
        .009551.
        .012773.
        .017082.
        .022845.
        .030552.
        .040859.
        .054643.
        .073077.
        .097730.
        .130700.
        .174792.
        .233759.
        .312618.
        .418081.
        .559123.
        .747745.
```

```
;energy decoding table

detbl   0
        .011878.
        .013736.
        .015885.
        .018370.
        .021244.
        .024567.
        .028411.
        .032855.
        .037995.
        .043939.
        .050813.
        .058762.
        .067955.
        .078586.
        .090880.
        .105097.
        .121538.
        .140552.
        .162540.
        .187968.
        .217373.
        .251379.
        .290705.
        .336183.
        .388776.
        .449596.
        .519931.
        .601269.
        .695332.
        .804109.
        .929905.
```

.6-bit k-parameter encoding table

lar 6	-.978244.	-.713578.
	-.976336.	-.692070.
	-.974263.	-.669258.
	-.972010.	-.645112.
	-.969564.	-.619603.
	-.966907.	-.592716.
	-.964023.	-.564439.
	-.960892.	-.534772.
	-.957494.	-.503725.
	-.953809.	-.471321.
	-.949812.	-.437591.
	-.945478.	-.402584.
	-.940782.	-.366358.
	-.935695.	-.328986.
	-.930187.	-.290555.
	-.924225.	-.251163.
	-.917776.	-.210920.
	-.910804.	-.169950.
	-.903270.	-.128384.
	-.895134.	-.086362.
	-.886355.	-.044030.
	-.876889.	-.001540.
	-.866691.	.040956.
	-.855712.	.083304.
	-.843905.	.125354.
	-.831219.	.166958.
	-.817605.	.207976.
	-.803010.	.248275.
	-.787385.	.287732.
	-.770677.	.326237.
	-.752838.	.363688.
	-.733820.	

```
;6-bit k-parameter decoding table

dlar 6  -.979140.           -.723855.
        -.977310.           -.702985.
        -.975320.           -.680829.
        -.973160.           -.657354.
        -.970812.           -.632529.
        -.968263.           -.606333.
        -.965494.           -.578751.
        -.962489.           -.549779.
        -.959228.           -.519420.
        -.955689.           -.487690.
        -.951851.           -.454619.
        -.947689.           -.420244.
        -.943178.           -.384619.
        -.938290.           -.347810.
        -.932996.           -.309897.
        -.927265.           -.270972.
        -.921064.           -.231140.
        -.914358.           -.190518.
        -.907109.           -.149233.
        -.899280.           -.107421.
        -.890828.           -.065226.
        -.881711.           -.022795.
        -.871885.           .019717.
        -.861302.           .062158.
        -.849915.           .104376.
        -.837675.           .146220.
        -.824531.           .187548.
        -.810433.           .228223.
        -.795330.           .268116.
        -.779169.           .307110.
        -.761902.           .345100.
        -.743480.           .381992.
```

```
;4-bit k-parameter encoding table

lar4    -.640421.
        .571990.
        -.494548.
        -.408367.
        -.314235.
        -.213490.
        -.107990.
        .0.
        .107990.
        .213490.
        .314235.
        .408367.
        .494548.
        .571990.
        .640421.

;4-bit k-parameter decoding table

dlar4   -.671294.
        -.607331.
        -.534389.
        -.452514.
        -.362224.
        -.264584.
        - 161200.
        -.054153.
        .054153.
        .161200.
        .264584.
        .362224.
        .452514.
        .534390.
        .607331.
        .671294.
```

```
;3-bit k-parameter encoding table

lar3    -.477592.
        -.333333.
        -.171573.
        .0.
        .171573.
        .333333.
        .477592.


;3-bit k-parameter decoding table

dlar3   -.541661.
        -.408006.
        -.254231.
        -.086427.
        .086427.
        .254230.
        .408006.
        .541661.


;2-bit k-parameter encoding table

lar2    -.333333.
        .0.
        .333333.


;2-bit k-parameter decoding table

dlar2   -.477592.
        -.171573.
        .171573.
        .477592.
```

```
; 8 bit lar table

;           k              ln(AR)                 k              ln(AR)
lartab  100000       ;0: -infinity       -0.937973.    ;32: -3.441836
        -0.979274.   ;1: -4.559081       -0.935770.    ;33: -3.405796
        -0.978521.   ;2: -4.523041       -0.933492.    ;34: -3.369756
        -0.977742.   ;3: -4.487000       -0.931135.    ;35: -3.333715
        -0.976934.   ;4: -4.450960       -0.928698.    ;36: -3.297675
        -0.976098.   ;5: -4.414920       -0.926178.    ;37: -3.261635
        -0.975232.   ;6: -4.378880       -0.923572.    ;38: -3.225595
        -0.974335.   ;7: -4.342840       -0.920879.    ;39: -3.189555
        -0.973405.   ;8: -4.306799       -0.918094.    ;40: -3.153514
        -0.972443.   ;9: -4.270760       -0.915216.    ;41: -3.117474
        -0.971446.   ;10: -4.234719      -0.912241.    ;42: -3.081434
        -0.970413.   ;11: -4.198679      -0.909167.    ;43: -3.045394
        -0.969344.   ;12: -4.162639      -0.905990.    ;44: -3.009354
        -0.968237.   ;13: -4.126599      -0.902708.    ;45: -2.973314
        -0.967091.   ;14: -4.090559      -0.899317.    ;46: -2.937274
        -0.965904.   ;15: -4.054519      -0.895815.    ;47: -2.901233
        -0.964675.   ;16: -4.018478      -0.892197.    ;48: -2.865193
        -0.963402.   ;17: -3.982438      -0.888462.    ;49: -2.829153
        -0.962084.   ;18: -3.946398      -0.884605.    ;50: -2.793113
        -0.960720.   ;19: -3.910358      -0.880623.    ;51: -2.757073
        -0.959308.   ;20: -3.874318      -0.876513.    ;52: -2.721032
        -0.957846.   ;21: -3.838278      -0.872270.    ;53: -2.684992
        -0.956333.   ;22: -3.802237      -0.867893.    ;54: -2.648952
        -0.954767.   ;23: -3.766197      -0.863376.    ;55: -2.612912
        -0.953146.   ;24: -3.730157      -0.858716.    ;56: -2.576872
        -0.951468.   ;25: -3.694117      -0.853910.    ;57: -2.540832
        -0.949732.   ;26: -3.658077      -0.848954.    ;58: -2.504791
        -0 947935.   ;27: -3.622036      -0.843844.    ;59: -2.468751
        -0.946076.   ;28: -3.585996      -0.838576.    ;60: -2.432711
        -0.944152.   ;29: -3.549956      -0.833146.    ;61: -2.396671
        -0.942162.   ;30: -3.513916      -0.827551.    ;62: -2.360631
        -0.940103.   ;31: -3.477876      -0.821787.    ;63: -2.324591
```

8 bit lar table (continued)

k	ln(AR)
-0.815849.	;64: -2.288550
-0.809734.	;65: -2.252510
-0.803438.	;66: -2.216470
-0.796957.	;67: -2.180430
-0.790287.	;68: -2.144390
-0.783424.	;69: -2.108350
-0.776365.	;70: -2.072309
-0.769106.	;71: -2.036269
-0.761642.	;72: -2.000229
-0.753971.	;73: -1.964189
-0.746089.	;74: -1.928149
-0.737992.	;75: -1.892109
-0.729676.	;76: -1.856068
-0.721139.	;77: -1.820028
-0.712377.	;78: -1.783988
-0.703388.	;79: -1.747948
-0.694167.	;80: -1.711908
-0.684713.	;81: -1.675868
-0.675023.	;82: -1.639827
-0.665094.	;83: -1.603787
-0.654924.	;84: -1.567747
-0.644512.	;85: -1.531707
-0.633855.	;86: -1.495667
-0.622951.	;87: -1.459627
-0.611800.	;88: -1.423586
-0.600401.	;89: -1.387546
-0.588752.	;90: -1.351506
-0.576853.	;91: -1.315466
-0.564704.	;92: -1.279426
-0.552306.	;93: -1.243386
-0.539658.	;94: -1.207346
-0.526762.	;95: -1.171305

k	ln(AR)
-0.513618.	;96: -1.135265
-0.500230.	;97: -1.099225
-0.486597.	;98: -1.063185
-0.472724.	;99: -1.027145
-0.458612.	;100: -0.991105
-0.444265.	;101: -0.955064
-0.429686.	;102: -0.919024
-0.414880.	;103: -0.882984
-0.399851.	;104: -0.846944
-0.384604.	;105: -0.810904
-0.369144.	;106: -0.774864
-0.353477.	;107: -0.738823
-0.337609.	;108: -0.702783
-0.321547.	;109: -0.666743
-0.305298.	;110: -0.630703
-0.288869.	;111: -0.594663
-0.272267.	;112: -0.558623
-0.255503.	;113: -0.522582
-0.238583.	;114: -0.486542
-0.221517.	;115: -0.450502
-0.204315.	;116: -0.414462
-0.186985.	;117: -0.378422
-0.169538.	;118: -0.342382
-0.151984.	;119: -0.306341
-0.134334.	;120: -0.270301
-0.116598.	;121: -0.234261
-0.098787.	;122: -0.198221
-0.080913.	;123: -0.162181
-0.062987.	;124: -0.126141
-0.045020.	;125: -0.090100
-0.027024.	;126: -0.054060
-0.009010.	;127: -0.018020

8 bit lar table (continued)

k	ln(AR)
0.009010.	;128: 0.018020
0.027024.	;129: 0.054060
0.045020.	;130: 0.090100
0.062987.	;131: 0.126141
0.080913.	;132: 0.162181
0.098787.	;133: 0.198221
0.116598.	;134: 0.234261
0.134334.	;135: 0.270301
0.151984.	;136: 0.306341
0.169538.	;137: 0.342382
0.186985.	;138: 0.378422
0.204315.	;139: 0.414462
0.221517.	;140: 0.450502
0.238583.	;141: 0.486542
0.255503.	;142: 0.522582
0.272268.	;143: 0.558623
0.288869.	;144: 0.594663
0.305298.	;145: 0.630703
0.321547.	;146: 0.666743
0.337609.	;147: 0.702783
0.353477.	;148: 0.738823
0.369144.	;149: 0.774864
0.384604.	;150: 0.810904
0.399851.	;151: 0.846944
0.414880.	;152: 0.882984
0.429686.	;153: 0.919024
0.444265.	;154: 0.955064
0.458612.	;155: 0.991105
0.472724.	;156: 1.027145
0.486597.	;157: 1.063185
0.500230.	;158: 1.099225
0.513619.	;159: 1.135265

k	ln(AR)
0.526762.	;160: 1.171305
0.539658.	;161: 1.207346
0.552306.	;162: 1.243386
0.564704.	;163: 1.279426
0.576853.	;164: 1.315466
0.588752.	;165: 1.351506
0.600401.	;166: 1.387546
0.611800.	;167: 1.423586
0.622951.	;168: 1.459627
0.633855.	;169: 1.495667
0.644512.	;170: 1.531707
0.654924.	;171: 1.567747
0.665094.	;172: 1.603787
0.675023.	;173: 1.639827
0.684713.	;174: 1.675868
0.694167.	;175: 1.711908
0.703388.	;176: 1.747948
0.712377.	;177: 1.783988
0.721139.	;178: 1.820028
0.729676.	;179: 1.856068
0.737992.	;180: 1.892109
0.746089.	;181: 1.928149
0.753971.	;182: 1.964189
0.761642.	;183: 2.000229
0.769106.	;184: 2.036269
0.776365.	;185: 2.072309
0.783424.	;186: 2.108350
0.790287.	;187: 2.144390
0.796957.	;188: 2.180430
0.803438.	;189: 2.216470
0.809734.	;190: 2.252510
0.815849.	;191: 2.288550

```
; 8 bit lar table (continued)

;          k                ln(AR)
        0.821787.    ;192:  2.324591
        0.827551.    ;193:  2.360631
        0.833146.    ;194:  2.396671
        0.838576.    ;195:  2.432711
        0.843844.    ;196:  2.468751
        0.848954.    ;197:  2.504791
        0.853910.    ;198:  2.540832
        0.858716.    ;199:  2.576872
        0.863376.    ;200:  2.612912
        0.867893.    ;201:  2.648952
        0.872270.    ;202:  2.684992
        0.876513.    ;203:  2.721032
        0.880623.    ;204:  2.757073
        0.884605.    ;205:  2.793113
        0.888462.    ;206:  2.829153
        0.892197.    ;207:  2.865193
        0.895815.    ;208:  2.901233
        0.899317.    ;209:  2.937274
        0.902708.    ;210:  2.973314
        0.905990.    ;211:  3.009354
        0.909167.    ;212:  3.045394
        0.912241.    ;213:  3.081434
        0.915216.    ;214:  3.117474
        0.918094.    ;215:  3.153514
        0.920879.    ;216:  3.189555
        0.923572.    ;217:  3.225595
        0.926178.    ;218:  3.261635
        0.928698.    ;219:  3.297675
        0.931135.    ;220:  3.333715
        0.933492.    ;221:  3.369756
        0.935770.    ;222:  3.405796
        0.937973.    ;223:  3.441836

          k                ln(AR)
        0.940103.    ;224:  3.477876
        0.942162.    ;225:  3.513916
        0.944152.    ;226:  3.549956
        0.946076.    ;227:  3.585996
        0.947935.    ;228:  3.622036
        0.949732.    ;229:  3.658077
        0.951468.    ;230:  3.694117
        0.953146.    ;231:  3.730157
        0.954767.    ;232:  3.766197
        0.956333.    ;233:  3.802237
        0.957846.    ;234:  3.838278
        0.959308.    ;235:  3.874318
        0.960720.    ;236:  3.910358
        0.962084.    ;237:  3.946398
        0.963402.    ;238:  3.982438
        0.964675.    ;239:  4.018478
        0.965904.    ;240:  4.054519
        0.967091.    ;241:  4.090559
        0.968237.    ;242:  4.126599
        0.969344.    ;243:  4.162639
        0.970413.    ;244:  4.198679
        0.971446.    ;245:  4.234719
        0.972443.    ;246:  4.270760
        0.973405.    ;247:  4.306799
        0.974335.    ;248:  4.342840
        0.975232.    ;249:  4.378880
        0.976098.    ;250:  4.414920
        0.976934.    ;251:  4.450960
        0.977742.    ;252:  4.487000
        0.978521.    ;253:  4.523041
        0.979274.    ;254:  4.559081
        0.980000.    ;255:  4.595121
        0.999999.
```

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18. SUPPLEMENTARY NOTES

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A detailed description of the implementation of a robust 2400 b/s LPC algorithm is presented. The algorithm was developed to improve vocoder performance in acoustically compromised environments. Improved robustness in noise is achieved by (1) increasing the speech bandwidth to 5 kHz, (2) increasing the LPC model order to 12, and (3) doubling the analysis rate. Frame fill techniques are used to achieve the 2400 b/s data rate. The algorithm is embodied in the Advanced Linear Predictive Coding Microprocessor which was developed as a prototype voice processor for in-flight evaluation of narrowband voice communication in the JTIDS communication system.